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High Average Power Yb:YAG Laser

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Abstract
We are working on a composite thin-disk laser design that can be scaled as a source of high brightness laser power for tactical engagement and other high average power applications. The key component is a diffusion-bonded composite comprising a thin gain-medium and thicker cladding that is strikingly robust and resolves prior difficulties with high average power pumping/cooling and the rejection of amplified spontaneous emission (ASE). In contrast to high power rods or slabs, the one-dimensional nature of the cooling geometry and the edge-pump geometry scale gracefully to very high average power. The crucial design ideas have been verified experimentally[1]. Progress this last year included: extraction with high beam quality using a telescopic resonator, a heterogeneous thin film coating prescription that meets the unusual requirements demanded by this laser architecture, thermal management with our first generation cooler. Progress was also made in design of a second-generation laser.

Introduction
With recent funding provided by the Joint Technology Office, our thin-disk laser project has gained momentum. We refer to this project as the "HiBriTE" laser an acronym for High Brightness Tactical Engagement. A new set of experiments has started and we report here a snapshot in time for the results of these ongoing tests while covering our planned tests. The recent experimental results give us confidence in our scalability and high brightness arguments. To affirm the viability of the concept, the first step is to demonstrate 300 W of sustained output. Beam quality issues at high average power are next in our agenda. Shown in Fig. 1 are the diode arrays, hollow lens ducts, and output coupler, in addition to a blow-up of the 15%Yb:YAG / YAG composite laser disk situated on the cooler (soldered with indium). The inset picture in figure 1 shows finished, diffusion-bonded Yb:YAG/YAG composite laser gain media we are using in our tests. This is the equipment we are testing. It has already produced 260 watts in low duty factor quasi-cw operation (~10%, 5 ms pulses) and 50 watts in true cw operation. With the hardware upgrades enabled by the new funding, we will demonstrate our average power goal of 300 watts and tractable high brightness by using a telescopic resonator[2]. We have already collected data with a telescopic resonator at low duty factor and have generated low order gaussian modes of predictable high beam quality. We are nearing similar tests at high average power.

The Thin Disk Advantage
One of the crucial advantages of the thin-disk design is that the thermal gradients are aligned with the beam propagation direction, so that they do not impart significant wavefront distortion onto the light field. To first order, the thin-disk laser geometry mitigates the effects of dn/dT and stress-optic effects. A second order effect remains, relating to the pump uniformity. Deformations previously were the main source of wavefront error in a thin-disk however, because "stiffness" is proportional to the cube of the thickness. A major advantage of our approach over conventional thin-disk lasers is therefore the diffusion bonded undoped cap serving as a "stiffness" member for the HiBriTE laser-disk, keeping the deformations to a minimum. We will present interferometry data of a thermally loaded thin-disk-composite laser element, which we plan to benchmark with our thermo-mechanical/optics calculations. Another advantage provided by the diffusion bonded cap is that it allows for side pumping with laser diodes. Last but not least, the index of refraction matched cap layer also provides a larger volume which dilutes spontaneous emission greatly diminishing the adverse impact of amplified spontaneous emission (ASE). There is no downside to the undoped cap which simply rises to a constant temperature and has no impact on the heat handling advantage of the thin disk.

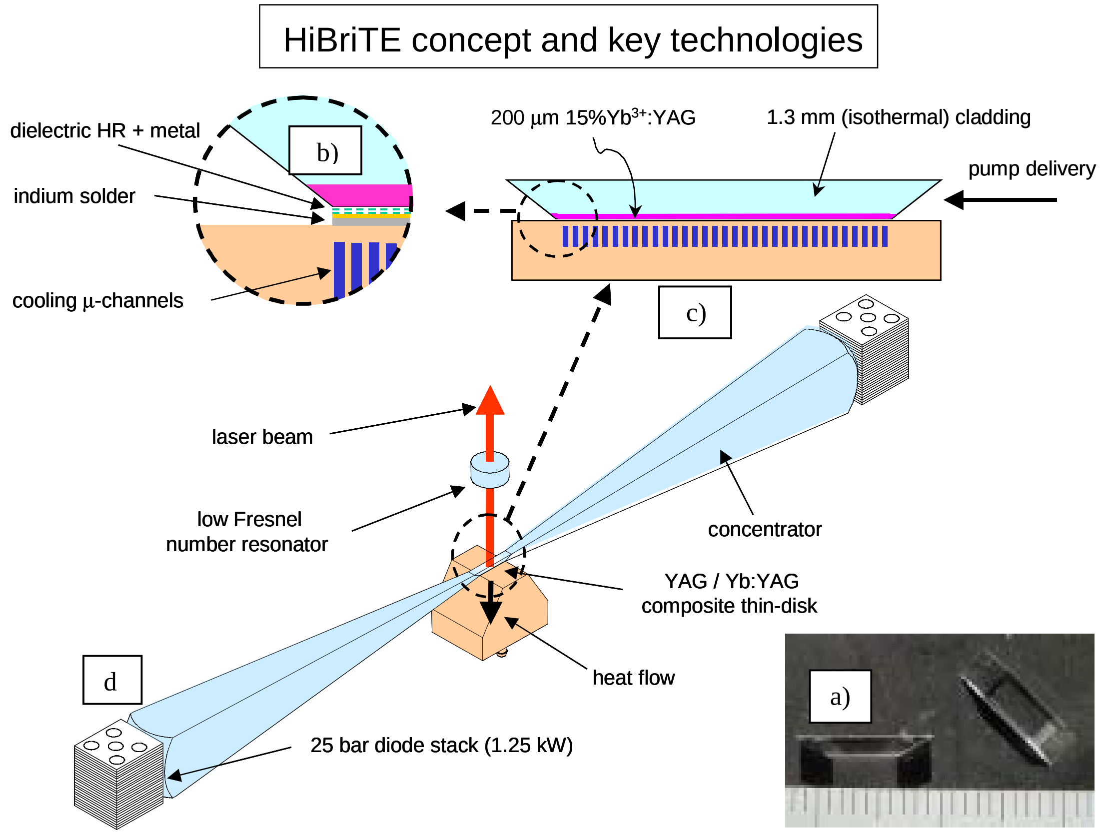

Figure 1.- The HiBriTE thin-disk-laser concept. The enabling technologies are depicted in this figure. (a) The Yb:YAG/YAG diffusion-bonded composite gain medium is cut and polished with specified shape; (b) a complex thin film coating we developed acts as the laser back-mirror and for pump containment, (c) Indium soldering conducts heat intensity $\geq$ 350 W/cm^2 to the c) high efficiency micro-channel cooler. (d) High brightness pump diodes and lens-duct pump delivery.

Initial experiments -Thermal management

The thin film coating was a subject of intense activity over the past year. Demands placed on the thin film by the unusual architecture are: 1) reflect at the laser wavelength (1030 nm) with high efficiency, 2) reflect diode pump light at 940 nm over a broad phase space, 3) be compatible with indium solder for low thermal impedance and 4) conduct a heat flux of 350 W/cm^2. Development took place in house. YAG coupons were coated with a dielectric stack followed by several metal films and finally an indium film prior to soldering to a gold coated CuW surface (similar to a cooler's surface). Two major problems were encountered: Adhesion of the metal film to the dielectric stack and eutectic mixing of indium with candidate metallic film during soldering. An additional metal film barrier was added to prevent indium migration during soldering. Adhesion of the films was taken care off by judicious choice of the metal films and surface activation via plasma sputtering of the dielectric surface prior to depositing the first metal layer. We now routinely coat and solder gain samples to coolers. We have tested one slab at a measured 590 W/cm^2 continuous heat flux with no signs of damage to the coatings.

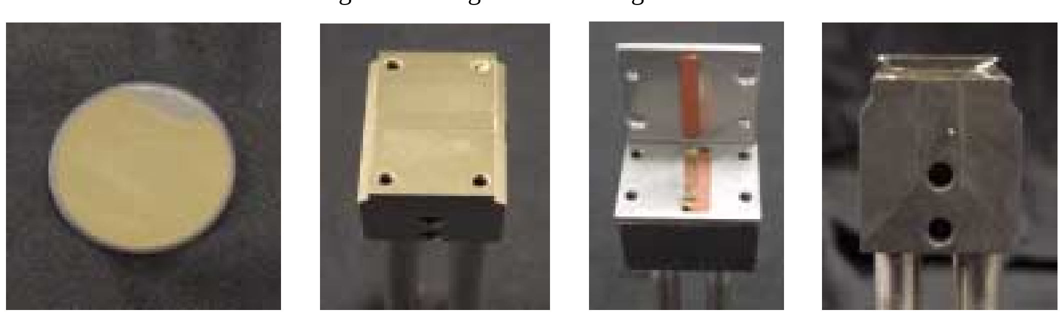

Figure 2. From left to right: first successful YAG coupon, ready cooler, precision solder fixture, fully coated slab and cooler tested at 590 W/cm^2 with no signs of damage.

Initial experiments –Beam quality

The characteristic one-dimensional thermal gradient of a thin-disk laser can be exploited if we make the transverse dimension of the laser aperture the principal means of scaling the average power output. High radiance is required for tactical engagement missions and therefore a resonator capable of extracting with beam quality is required. Unstable resonators are not a good choice due to intrinsically low gain through the thin dimension of the gain medium. Since a high gain to loss ratio is required for efficient laser extraction, the resonator transverse mode must have low loss. The resonator Fresnel number $N_f = a^2/(L\cdot\lambda)$ (where a is the aperture radius and L the cavity length), determines the highest order Gaussian mode that can oscillate without significant diffractive loss ($N_{max} = \pi\cdot N_f$ for a confocal resonator). A cavity with low Fresnel number is desired however; it is not practical to use the length of the resonator for mode selection. An intra-cavity telescope was first proposed by Steffen et al. and later analyzed and experimented upon by

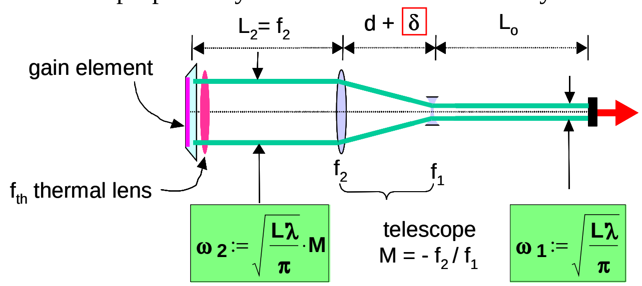

Figure 3- The telescopic resonator. The simple solutions of the special case shown above are both useful and illustrative. The thermal lens is considered attached to the back-mirror. The parameter δ is adjusted to compensate for thermal lensing as well as to bring it into stability.

Hanna[3]. A dynamically stable resonator with an effective length $M^2\cdot L_o$ can be realized (where L_o is the length at the small beam end of the cavity and M is the telescope magnification). Figure 3 shows the key features of the telescopic resonator. The telescopic resonator is an attractive choice for the HiBriTE laser for several reasons. One is the ability to easily adjust for thermal lensing under varied pumping conditions.

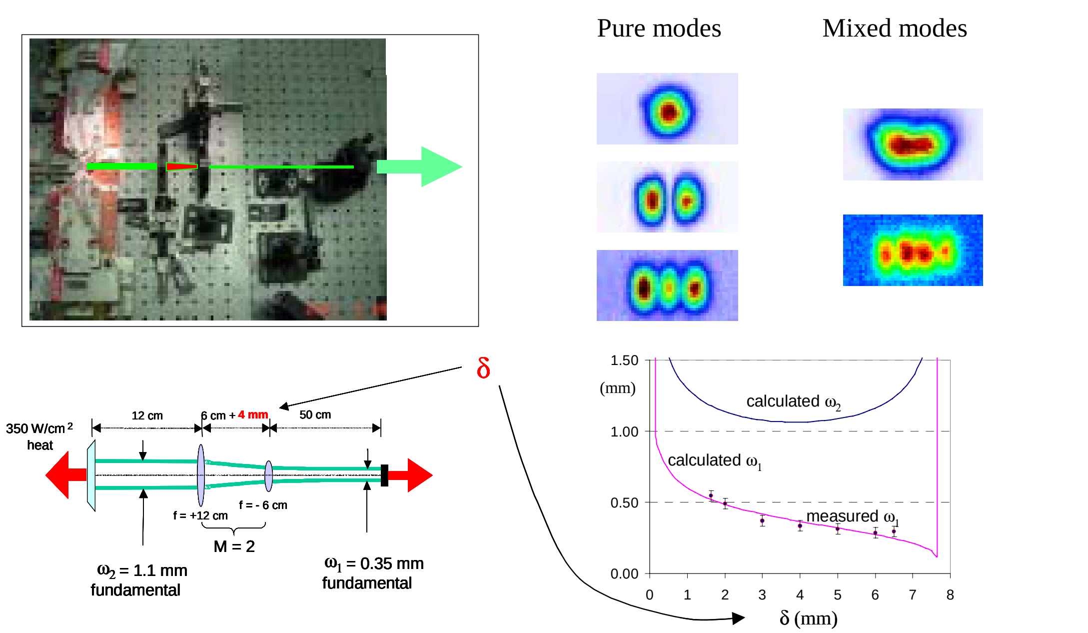

Figure 4 –Clockwise from the top-left corner: top view picture of the HiBriTE laser and intracavity (Galilean) telescope; a sample of output modes ranging from $TEM_{o,o}$ to $TEM_{4,1}$ obtained adjusting the output coupler tilt for a given L_o and δ. The mixed modes were more prevalent away from $g_1\cdot g_2=½$; the measured (vertical) beam parameter (ω_2) at the output coupler (the only one accessible) was compared to the theory; The desired operating stability point is found for operation.

Another, as Hanna showed in his appendix, is that once adjusted, the diffraction losses produced are those of an equivalent confocal resonator, which offers the greatest degree of mode selectivity and insensitivity to thermal fluctuations. Figure 4 summarizes our initial experiments calibrating our laboratory telescopic resonator and verifying its mode selectivity. Experiments at average power will verify the dynamically stable operation of this resonator in the near future.

Progress with a second generation design

The scaling to truly high average powers requires optical isolation "grooves" between gain "islands". The optically-passive volume adjacent to the gain-sheet drastically reduces the solid angle factor available for the internal fluorescence to experience gain however, there is a maximum laser aperture size that is limited by ASE due to unconfined photons traveling transversely within the thin gain medium. This aperture can be increased by strategically cut "grooves" into the thin material but not penetrating the "cap-disk". We feel encouraged by the data and believe that our thin-disk laser designs will enable a new class of high beam quality, high average power lasers. The future holds promise. We have calculated that a single ASE limited aperture based on YbAG should enable up to 8 kW of laser power while >100 kW can be envisaged based on near contiguous placement of several such apertures. A reasonable next step in the near term based on standard 15%Yb:YAG was also investigated computationally. Figure 5 shows an ASE limited design with a hexagonal cross section pumped from 6 sides. The absorbed power distribution computed (ray-trace) peaks in the center of the aperture. The design can be optimized for efficient extraction when coupled with the suitable low order mode of a telescopic resonator. Work by UC/LLNL for DOE(W-7405-Eng-48).

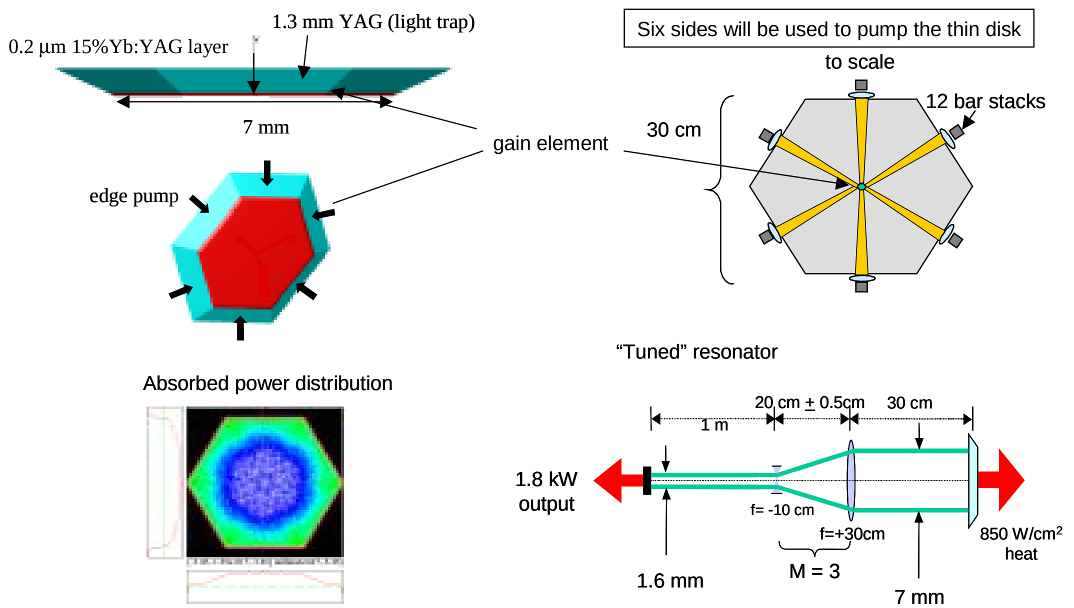

Figure 5- A reasonable next step using available crystals would be the ASE limited design shown here.

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[1] Luis E. Zapata, Raymond J. Beach and Stehen A. Payne, Lawrence Livermore National Laboratory ,"Composite Thin-Disk Laser Scaleable to 100 kW Average Power Output and beyond", SSLDTR-2000 Technical Digest

[2] D. C. Hanna, C. G. Sawyers, M. A. Yuratich, University of Southhampton, UK, "Telescopic resonators for large-volume TEMoo – mode operation", Optical and Quantum Electronics 13 (1981) 493-507

[3] J. Steffen, J. P. Lortscher and G. Herziger, ibid QE-8 (1972) 239-45